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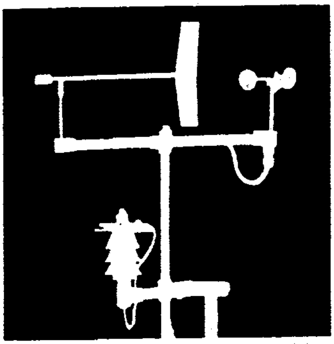
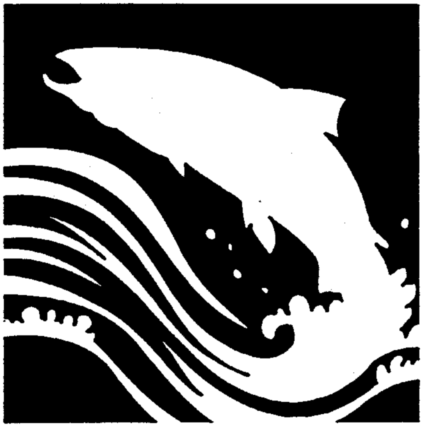
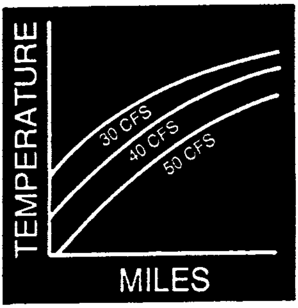


# Guidance for Evaluating and Recommending Temperature Regimes to Protect Fish

Instream Flow
Information Paper 28



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# Guidance for Evaluating and Recommending Temperature Regimes to Protect Fish

## Instream Flow Information Paper 28

By

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# Contents

# Preface

Temperature regimes of flowing water are affected by several factors including flow, shade, and channel morphology. Stream alterations that change temperature regimes and affect fish can be difficult to evaluate. This document will aid biologists in analyzing temperature regimes and preparing tèchnically defensible recommendations for fish protection. This report includes an explanation of basic temperature tolerance relations plus three options for developing recommendations. Although examples in the document pertain to spring chinook salmon, the principles apply to all fish species.

# Guidance for Evaluating and Recommending Temperature Regimes to Protect Fish

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**Abstract.** Procedures are presented for evaluating temperature regimes for fish. Although examples pertain to spring chinook salmon (*Oncorhynchus tshawytscha*), the principles apply to other species. Basic temperature tolerance relationships for fish are explained and three options are described for comparing alternative temperature regimes. The options are to base comparisons on experimental temperature tolerance results, suitability of a simulated temperature regime for key life stages, or population statistics and predicted responses to simulated temperatures.

**Key words:** Chinook salmon, water temperature, alternative temperature regimes.

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Water temperature is one of the most important environmental factors affecting fish (Fry 1967, 1971; Hutchinson 1976). For example, temperature regimes influence migration, egg maturation, spawning, incubation success, growth, inter- and intraspecific competitive ability, and resistance to parasites, diseases, and pollutants. A major problem hindering precise understanding of temperature effects is that many environmental factors may influence fish simultaneously (Fig. 1). Furthermore, some factors function synergistically, which consequently masks the influence of individual relations.

When general temperature requirements are considered, fish can be grouped into coldwater, coolwater, or warmwater categories (Table 1). Hokanson and Biesinger (unpublished report) reported the highest mean weekly temperatures in the field. For 95% of the data sets, the highest average mean weekly temperatures for coldwater, coolwater, and warmwater species were approximately 22° C, 29° C, and 30° C, respectively. The levels of success and health of the fish were not documented, so one cannot assume that the temperatures represent each category's upper limits for success. For example, 22° C would be considered excessive for reproduction and prolonged success of salmonids. Conversely, certain warmwater species can reproduce and survive temperatures higher than 30° C. Piper et al. (1982) reported that coldwater species generally spawn in temperatures below 12.8° C, coolwater species in temperatures between 4.4° C and 15.6° C, and warmwater species above 15.6° C. This information demonstrates a need for evaluating temperature requirements for each species because generalities are too imprecise.

Three options for developing temperature regimes to protect fish are described here, based primarily on experimental temperature tolerance results, suitability of regimes for key life stages, and population statistics and predicted responses to simulated temperatures.

Recommendations derived from these options may be applied to streams that are or will be affected by channel modifications, diversions, reservoir releases, or adjoining land-use practices such as vegetation removal, all of which may alter temperature regimes. Although examples pertain to spring chinook salmon (*Oncorhynchus tshawytscha*), the principles apply to other fish species. Information presented here can be used in conjunction with temperature studies described in *Instream Flow Information Paper* 13 (Bartholow 1989).

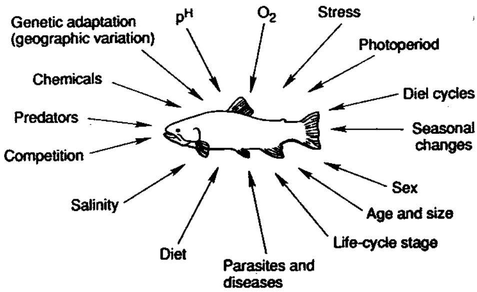


**Fig. 1.** Some examples of factors that can influence the response of fish to temperature regimes. The information is modified from Hutchinson (1976).

Temperature tolerances can be displayed in a polygonal pattern (Fig. 2) indicating loading level and inhibiting level zones (Fig. 3). Definitions of terms associated with the polygons follow.

**Acclimation temperature.** Temperature in the tolerance zone that test fish are experimentally exposed to for several days before a tolerance test.

**Upper incipient lethal temperature (UILT).** The upper temperature that 50% mortality is observed for a given acclimation temperature. The UILT increases with acclimation temperatures to a point that higher acclimation temperatures have no effect.

**Lower incipient lethal temperature (LILT).** The lower temperature that 50% mortality is observed for a given acclimation temperature.

**Upper ultimate incipient lethal temperature (UUILT).** The highest temperature at which tolerance does not increase with increasing acclimation temperatures. On a polygon, this temperature is constant and parallel to the acclimation temperature axis.

**Temperature of instantaneous death (TID).** Temperature outside the tolerance zone at which death is instantaneous.

**Acute thermal preferendum (AP).** Initial choice of acclimation temperature following acclimation of a given temperature.

**Line of equality (LE).** Line at a 45° angle to the temperature acclimation axis representing equality of acclimation and response temperatures.

**Final preferendum (FP).** Eventual choice of temperature zone irrespective of acclimation history.

Table 1. *Some examples of fish that can be grouped into coldwater, coolwater, or warmwater categories.*

| Coldwater | Coolwater | Warmwater |
|---|---|---|
| Brook trout | Northern pike | Bluegill |
| Brown trout | Sauger | Brown bullhead |
| Chinook salmon | Walleye | Channel catfish |
| Coho salmon | Yellow perch | Flathead catfish |
| Mountain whitefish | | Gizzard shad |
| Pink salmon | | Largemouth bass |
| Rainbow trout | | Smallmouth bass |
| Sockeye salmon | | |

# Option 1: Experimental Temperature Tolerance Results

Experimental temperature results for a species (Table 2) can be used with simulated (predicted) temperatures for a new regime to evaluate possible effects. If this option is implemented, however, caution is necessary because experimental results can be affected by other factors, including fish size, season, day length, sex, and water chemistry (Coutant 1970), or by disease, genetic variation, and the life cycle stage (Fig. 1). For some species temperature requirements of juveniles and adults vary considerably. This variation often causes the age groups to select different habitat types.

Three additional definitions from terms in Table 2 will establish the basis for equations that are used in Option 1.

**Growth optimum (GO).** Temperature under experimental conditions at which growth rates, expressed as weight gain per unit of time, are maximal for the life stage.

**Zero net growth (ZNG).** Temperatures under experimental conditions at which instantaneous growth and mortality rates for populations are equal. Growth rates are considered to be an overall indicator of environmental quality and seemingly are the most sensitive of various performance functions, particularly if expressed as zero net growth when food is not limiting (Brungs and Jones 1977).

**Physiological optimum (PO).** Temperature under experimental conditions approximating that for optimum growth, stamina, heart performance, and other func-

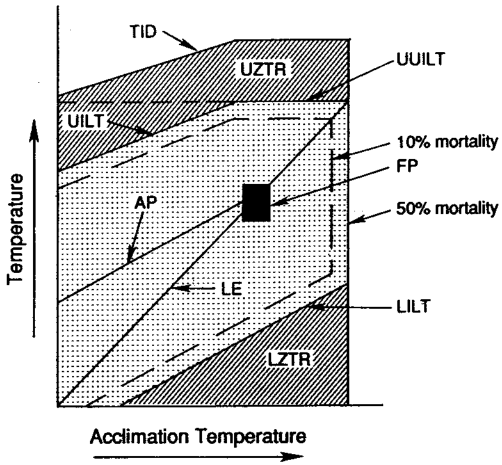


Fig. 2. Temperature tolerance responses for a hypothetical fish. The *dotted* area represents the zone of thermal tolerance (Brett 1960; Coutant 1970; Jobling 1981). AP = acute thermal preferendum, LE = line of equality, LILT = lower incipient lethal temperature, FP = final preferendum, UUILT = upper ultimate incipient lethal temperature, TID = temperature of instantaneous death, LZTR = lower zone of thermal resistance, and UZTR = upper zone of thermal resistance. The responses can vary within and between species because of genetic differences, environmental influences, and other factors, including the life stage. The area bounded by the 50% mortality line is the zone of thermal tolerance.

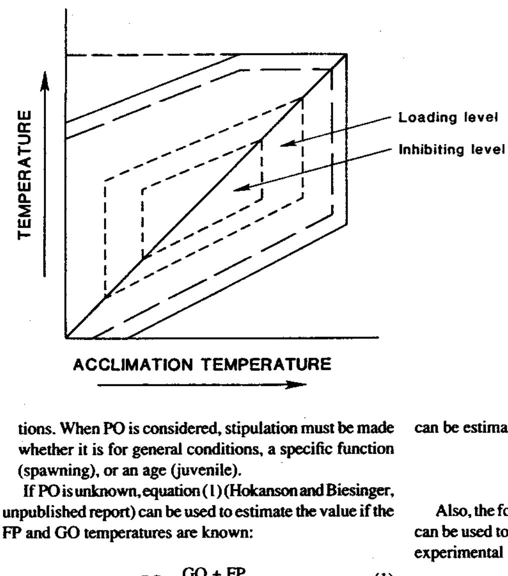


Fig. 3. Temperature polygon for a hypothetical fish with loading level and inhibiting zones. Normal reproduction occurs within the inhibiting level zone compared to normal growth within the loading level zone (Brett 1960).

tions. When PO is considered, stipulation must be made whether it is for general conditions, a specific function (spawning), or an age (juvenile).

If PO is unknown, equation (1) (Hokanson and Biesinger, unpublished report) can be used to estimate the value if the FP and GO temperatures are known:

$$PO = \frac{GO + FP}{2}. \qquad (1)$$

Accordingly, if any two variables are known, the third can be estimated by rearranging the equation:

$$GO = 2PO - FP.$$

Also, the following regression equations (Jobling 1981) can be used to estimate values for equation (1) variables if experimental information is available:

$$FP = (1.05)(GO) - 0.53, \qquad (2)$$
$$UUILT = 0.76\,(GO) + 13.81, \text{ and} \qquad (3)$$
$$UUILT = 0.66\,(FP) + 16.43. \qquad (4)$$

Table 2. *Experimental temperature response data for juvenile chinook salmon.*

| Acclimation temperature (° C)[a] | Temperature for 50% mortality (° C)[a] Upper | Lower |
|---|---|---|
| 5.0 | — | 21.5 |
| 10.0 | 0.8 | 24.3 |
| 15.0 | 2.5 | 25.0 |
| 20.0 | 4.5 | 25.1 |
| Growth optimum (° C) | 14.8 (Brett et al. 1982) | |
| Zero net growth (° C) | 19.1 Upper (Hokanson and Biesinger, unpublished report)[b] | |
| | 4.5 Lower (Hokanson and Biesinger, unpublished report)[b] | |
| Final preferendum (° C) | 11.7 (Hokanson and Biesinger, unpublished report)[b] | |
| Physiological Optimum (° C) | 13.6 (Hokanson and Biesinger, unpublished report)[b] | |

[a]From thermal tables in Coutant (1972)
[b]The authors did not indicate race, but the values presumably would be representative for spring chinook salmon.

Respective $r$ values for equations (2), (3), and (4) are 0.937, 0.866, and 0.880 (Jobling 1981). These relatively high values indicate that a good linear relation exists between variables in the equations.

Examples of temperature regime evaluations that could be made, based on those reported by Coutant (1972) and Brungs and Jones (1977), are described as follows.

## *Maximum Weekly Average Temperature (MWAT) That Should not be Exceeded*

Experimental temperature information is a prerequisite for an MWAT evaluation, and the information must be available for a specific life stage (e.g., juvenile rearing; Table 2).

The equation for an MWAT calculation is:

$$\mathrm{MWAT} = \mathrm{OT} + \frac{\mathrm{UUILT} - \mathrm{OT}}{3}, \tag{5}$$

where

OT = a reported optimal temperature for the particular life stage or function, and

UUILT = the upper temperature that tolerance does not increase with increasing acclimation temperatures (Fig. 2).

If OT is unknown, the midpoint of a recommended range can be used as an approximation. For example, Wilson et al. (1987) reported that 10.8° C is the midpoint of the recommended range for growth of juvenile chinook salmon. By substituting 10.8 for OT in equation (5) and assuming UUILT to correspond to the highest lethal threshold (25.1° C; Table 2) a conservative MWAT is calculated as follows:

$$\mathrm{MWAT} = 10.8 + \frac{25.1 - 10.8}{3},$$
$$= 10.8 + 4.8 = 15.6° \mathrm{C}.$$

Brett et al. (1982) reported an optimal midpoint of recommended range of 14.8° C under experimental conditions. With this value, MWAT = 18.2. This exceeds 16° C that Reiser and Bjornn (1979) reported as the upper range limit for Alaska fish that possibly require lower temperatures.

The interpretation of MWAT is that a calculated value based on experimental data is the upper temperature recommended for a specific life stage. The MWAT criterion can be used to evaluate the acceptability of temperatures for different site conditions (e.g., alternative flow regimes). For a hypothetical example, mean weekly maximum temperatures could be simulated for alternative stream flows (Table 3). Then, a check could be made to predict if the MWAT of 15.6° C for spring juvenile chinook salmon would be exceeded; MWAT would be exceeded for the 950 cfs flow.

## *Short-term Maximum (STM) Survival Temperature*

Short-term maximum (STM) is the maximum temperature, based on experimental data, that 50% of the fish could survive for a short time (i.e., 24 h or less); it is the same as the incipient lethal temperature. The value can be estimated by using the equation (Brungs and Jones 1977):

$$\mathrm{STM} = \frac{\log \text{ of time} - a}{b}. \tag{6}$$

Table 3. *Use of the MWAT criterion to evaluate temperatures for spring juvenile chinook salmon.*

| | Alternative flows (cfs) 1,500 | 1,200 | 950 |
|---|---|---|---|
| Simulated mean weekly maximum temperature (° C) | 14.2 | 14.9 | 19.7 |
| Is MWAT exceeded? | No | No | Yes |

Time is in minutes and $a$ and $b$ are regression equation constants from experimental studies (Table 4).

Since equation (6) expresses 50% survival for a given acclimation temperature, a 2° C safety margin, as suggested by Coutant (1972), can be subtracted from the STM temperature to derive the predicted value for 100% survival (Table 4).

$$\mathrm{STM} = \frac{\log \text{time} - a}{b} = \frac{\log \text{time of } 1{,}440 \text{ min} - 9.3155}{-0.3107},$$
$$= \frac{3.1584 - 9.3155}{-0.3107},$$
$$= 19.8° \text{ C}.$$

One application of the STM criterion could be to evaluate the acceptability of simulated temperatures for alternative flow regimes. For a hypothetical example, suppose the acclimation temperature for spring juvenile chinook salmon is about 10° C and the theoretical STM for 100% survival is 21.9° C (Table 4). Based on simulated 24-h maximum temperatures for alternative flows (Table 5), the predicted survival would be less than 100% for 950 cfs because the STM would be exceeded.

Table 4. *Temperature data for spring juvenile chinook salmon.*

| Acclimation temperature (° C)[a] | $a$ | $b$ | Calculated short-term maximum exposure temperature (° C)[b] | Short-term temperature for 100% survival (° C)[c] |
|---|---|---|---|---|
| 5 | 9.3155 | −0.3107 | 19.8 | 17.8 |
| 10 | 16.4595 | −0.5575 | 23.9 | 21.9 |
| 15 | 16.4454 | −0.5364 | 24.8 | 22.8 |
| 20 | 22.9065 | −0.7611 | 26.0 | 24.0 |
| 24 | 18.9940 | −0.5992 | 26.4 | 24.4 |

[a]Information from thermal tables in Coutant (1972).
[b]Must be calculated, that is, the STM value for 5° C is shown below.
[c]Must be calculated, for example, value for 19.8° C = 19.8 − 2 = 17.8° C.

Table 5. *Use of the STM criterion to evaluate temperature for spring juvenile chinook salmon.*

| | Alternative flows (cfs) 1,500 | 1,200 | 950 |
|---|---|---|---|
| Simulated 24-h maximum temperature (° C) | 16.5 | 16.9 | 23.6 |
| Is STM exceeded? | No | No | Yes |

## *Estimation of Lethality of an Exposure Time*

Equation (6) can be rearranged (Coutant 1972) to estimate if a given short-time exposure would be lethal:

$$1 \geqslant \frac{\text{time}}{{}_{10}[a + b\,(\text{temperature } ° \text{C} + 2° \text{ C})]} \qquad (7)$$

If the calculated value is equal to or less than 1, the exposure would not be lethal. As an example of using equation (7), $a$ and $b$ values (Table 4) for the 15° C acclimation temperature are 16.4454 and −0.5364, respectively. Assuming that juvenile chinook salmon would be exposed for 6 h (360 min) to a temperature of 27° C, the calculation would be:

$$\frac{360}{{}_{10}16.4454 + (-0.5364)(27+2)} = \frac{360}{{}_{10}16.4454 - 15.55\,56}$$
$$= \frac{360}{{}_{10}0.8898} = \frac{360}{7.7589} \text{ or } 46.3983.$$

Because 46.3983 is greater than unity, this exposure would probably be lethal. This conclusion is supported by the experimental results of Brett (1952), who found that the UUILT was 25.1° C (Table 2).

## *Survival Time for an Exposure Temperature*

The expected survival time at 27° C with 50% mortality for fish acclimated at a given temperature can be estimated by the following equation (Coutant 1972; Brungs and Jones 1977):

$$\log(\text{time}) = a + b\,(\text{temperature}) \qquad (8)$$

where $a$ and $b$ are mean regression constants (Table 4). For fish acclimated at 15° C, using this equation would result in:

$$\begin{aligned} \log(\text{time}) &= 16.4454 + (-0.5364)(27), \\ &= 16.4454 - 14.4828, \\ &= 1.9626, \\ \text{time} &= \text{antilog } 1.9626, \\ &= 91.7 \text{ min before reaching 50\% predicted mortality.} \end{aligned}$$

If Coutant's (1972) margin of safety of 2° C is used to estimate the time that fish could tolerate the exposure without mortality, the value with modification of equation (8) would be:

$$\log(\text{time}) = 16.4454 + (-0.5364)(27+2),$$

$= 16.4454 - 15.5556,$
$= 0.8898,$
time $= \text{antilog}\ (0.8898) = 7.8$ min.

## Option 2: Suitability of a Simulated Temperature Regime for Key Life Stages

Prerequisites for implementing this option are availability of temperature requirement information needed to evaluate life stages and simulated temperatures for a potential stream-alteration action. To aid in assembling temperature requirement information, the use of a bibliography prepared from the U.S. Fish and Wildlife Service, *Sport Fishery Abstracts*, a handbook pertaining to effects of temperature (Brown 1974), and U.S. Environmental Protection Agency documents (Hokanson and Biesinger, unpublished report; Brungs and Jones 1977) is recommended. A considerable amount of the material in Brungs and Jones (1977) was originally reported by Coutant (1972).

The U.S. Fish and Wildlife Service Habitat Suitability Index (HSI) models and suitability index curves can be other valuable information sources. For example, the HSI model by Raleigh et al. (1986) contains temperature information for chinook salmon.

After compiling temperature requirement information (Table 6), a simulated temperature regime can be evaluated to determine compatibility with ranges and tolerances for key life stages (Fig. 4). Presumably, temperatures outside the tolerance range would be harmful and are to be avoided.

The reproduction period (inhibiting zone) is the most restrictive, spawning and incubation temperatures should be a prime concern (Fig. 3). Chinook salmon can tolerate a wide range of temperatures during this period, which indicates a possible genetic adaptation. Olson and Foster (1955) subjected eggs of fall chinook salmon to five temperature regimes. The regime corresponding to the normal seasonal trend was the control. One regime averaged 2.2° C below the control, and the other three averaged 1.2° C, 2.3° C, and 4.6° C higher than the control. For the first three test groups and the control, the highest egg mortality was 8.7%; total mortality to the fingerling stage averaged 11.1%. At the highest temperature, 4.6° C higher than the control, egg mortality was 10.8%, and total mortality to the fingerling stage was 79.0%. These results suggested to Olson and Foster (1955) that the higher temperature regime damaged embryos and caused delayed mortality.

As an example of interpreting information, the simulated regime (Fig. 4) would exceed recommended upper temperatures and tolerances during the entire adult migration period. Also, tolerance values would be exceeded from spawning to the initial incubation period until about mid-October, compared to adverse temperatures for rearing from mid-May to mid-October. This information leads to the conclusion that the regime would be unsuitable for salmon.

Table 6. *Examples of temperature information that can be compiled for key spring chinook salmon life stages.*

| Stage | Temperature | Range |
|---|---|---|
| Adult migration | 3.3–13.3° C | Recommended[a] |
| | 2.0–16.0° C | Tolerance[b] |
| Spawning | 5.6–13.9° C | Recommended[a] |
| | 5.0–14.0° C | Tolerance[b] |
| Incubation | 5.0–14.4° C | Recommended[a,d] |
| | 0.0–16.0° C | Tolerance[b] |
| Juvenile rearing | 7.9–13.8° C | Recommended[a] |
| | 2.0–16.0° C | Tolerance[b] |
| Other | • Spawning run adults become susceptible to lethal diseases when temperatures attain 16.0° C (Snyder and Blahm 1968)<br>• 850 daily temperature units required for hatching[c]<br>• 700 daily temperature units required beyond hatching for emergence from gravel[c]<br>• Juvenile fish cannot tolerate temperatures exceeding 25.1° C for a 1-week period (Brett 1952)<br>• Adult spawning migrations are blocked at temperatures exceeding 21.0° C (Major and Mighell 1967)[e] | |

[a]Reiser and Bjornn (1979).
[b]Wilson et al. (1987).
[c]Thomas Levendofske, Superintendent of Rapid River Hatchery, Riggins, Idaho, personal communication.
[d]4.5–12.8° C required from the outset of incubation for a period > 2 weeks but ≤3.5 weeks for good embryo survival (Brett 1952).
[e]Reported for sockeye salmon but assumed to apply.

For an application of the option, temperature curves could be simulated for alternative flow regimes. Then, comparative information could be tabulated for designating an acceptable flow. For a hypothetical example, temperatures for 950 cfs would be unsuitable for all life stages compared to 1,200 cfs being unsuitable for incubation (Table 7).

If experimental tolerance data (e.g., data for the rearing stage) and durations of extreme temperatures are available, evaluations of possible effects could be made by using equations presented for Option 1. For example, suppose that during the second week in August, temperatures of 20.0° C would occur for a 24-h period, but the weekly

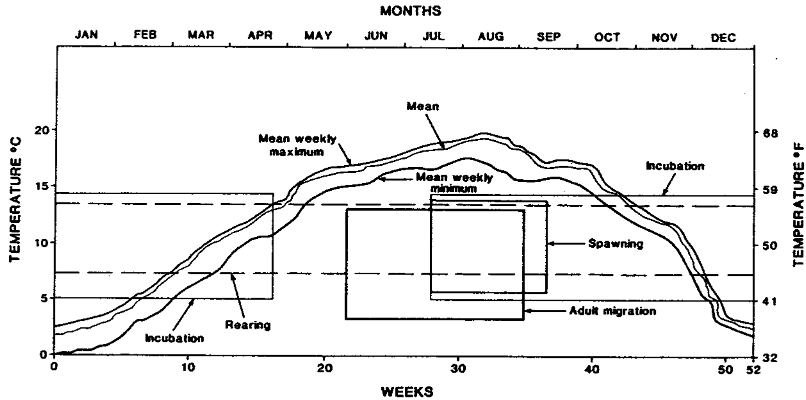


Fig. 4. Simulated mean maximum and mean temperatures for a hypothetical spring chinook salmon stream. Recommended temperatures *(rectangles)* for key stage periods are shown. Timeframes for the periods vary, and this type of information should be assembled for a specific stream or geographic area through consultation with experts.

mean temperature would be 14.5° C. This mean would not exceed the MWAT value for rearing (15.6° C) calculated with equation (5). Furthermore, 100% survival would be expected during the 24 h when the temperature would be 20.0° C because the critical temperature, as predicted by using equation (6) and adjusting with the 2° C safety factor, is 22.8° C for acclimation at 15° C. Because the upper tolerance limit of 16° C for rearing (Fig. 4) would be exceeded for a 24-h period, some form of stress could cause delayed effects.

Besides using this option as a basis for evaluating altered temperatures, some effects can be quantified. The following are some examples of quantification.

## *Estimation of Effects of a Spawning Migration Blockage*

Assume a spawning migration blockage is predicted (temperature would exceed 21° C; Table 6) in a zone downstream of a spawning and rearing area, and through consultations with experts, information pertaining to reproductive success was assembled (Table 8). With use of the information and equation (9), effects of the block on the future run size (FRS) could be estimated:

$$FRS = (RS)(BSR)(S)(NF)(F)(ES)(SRA). \quad (9)$$

Table 7. *Tabulations for comparing the acceptability of temperatures for three flow regimes for juvenile spring chinook salmon.*

| Life stage | Alternative flows (cfs) 1,500 | 1,200 | 950 |
|---|---|---|---|
| Adult migration | S[a] | S | U[b] |
| Spawning | S | S | U |
| Incubation | S | U | U |
| Rearing | S | S | U |

[a]S = suitable temperatures.
[b]U = unsuitable temperatures.

Table 8. *Hypothetical assumptions for reproductive success of spring chinook salmon. The assumptions are for illustration purposes because values vary on a stream-specific basis.*

- Returning adults to the spawning ground that spawn successfully = 80%
- 50:50 sex ratio
- Mean fecundity of 3,900 eggs per female
- 75% of eggs survive to fry stage
- 15% of fry survive to smolt stage
- Overall survival from egg to smolt stage is 10%
- Assume that 1% of smolts return as adults

where

FRS = future run size,
RS = run size to stream vicinity,
BSR = survival rate from effects of the run blockage,
S = percent of survivors that spawn,
NF = percent of run that is female,
F = mean female fecundity,
ES = egg to smolt survival rate, and
SRA = smolt to returning adult survival rate.

Assume experts agree that the spawning-run block would cause 20% mortality from disease and predation to the 250 adults (RS) that migrated to the area. This information would be used with equation (9) to estimate FRS as follows:

$$FRS = (250)(0.8)(0.8)(0.5)(3{,}900)(0.1)(0.01) = 312 \text{ adults.}$$

## Estimation of Emergence Time

After hatching, young chinook salmon emerge from the gravel to rear, and the time of hatching is controlled by the temperature regime. Development from fertilization to hatching requires 850 daily temperature units (DTU's), and an additional 700 units are required from hatching to beginning of emergence (Table 6). One DTU equals 1° above freezing (32° F) for a 24-h period (Piper et al. 1982). For example, if during a 24-h period the temperature is 37° F (2.8° C), this would equate to 37–32 or 5 DTU's. This type of information can be used to determine if initiation of fry emergence would occur before or during spring flooding (e.g., peak runoff is estimated to occur in late April for a hypothetical stream) that could result in the flushing and loss of young fish. Because the beginning of emergence is estimated at 1,550 DTU's, regime B (Table 9) would be in danger of losing fry. This would be attributed to exceeding 1,550 DTU's before late April. Furthermore, the date for initiation of emergence is 19 April. The rationale for reaching this date is that April has 210 DTU's or 7 DTU's per day. Because 130 DTU's are required beyond the end of March, 19 days would be required:

$$\frac{130}{7} = 18.6 \textit{ or } 19 \text{ days.}$$

## Estimation of Juvenile Fish Growth and Size at a Critical Period

Growth of juvenile chinook salmon, based on monthly thermal units (MTU's), could be estimated. One MTU is defined as the mean monthly temperature minus 32° on the Fahrenheit scale (Piper et al. 1982).

*Step 1.* Calculate monthly MTU values. Suppose that for February the mean temperature is 39° F; MTU's = 39 – 32 or 7 units.

*Step 2.* Calculate MTU's per centimeter of growth per month. Suppose that for the stream or through use of hatchery growth records it is known that the fish grew 0.71 cm in February. The MTU's per centimeter = MTU's per month ÷ centimeter of gain = 7/0.71 = 9.9 MTU's. If growth information (MTU's per centimeter of gain) is unavailable for a stream and hatchery data are used, caution must be exercised because growth for a given temperature regime also depends on food availability and other factors. Therefore, MTU's per centimeter of growth might be lower in a hatchery than in a stream because more food could be available. Also, a larger percentage of the total

Table 9. *Temperature unit data for two flow regimes for a hypothetical spring chinook salmon stream. It was assumed that spawning occurred on 15 August.*

| Month | X daily temperature (° F) for regimes A | B | Days in month | Temperature units for regimes A Monthly | A Cumulative | B Monthly | B Cumulative |
|---|---|---|---|---|---|---|---|
| August | 45 | 47 | 16 | 208[a] | 208 | 240 | 240 |
| September | 38 | 40 | 30 | 180 | 388 | 240 | 480 |
| October | 37 | 39 | 31 | 155 | 543 | 217 | 697 |
| November | 36 | 38 | 30 | 120 | 663 | 180 | 877 |
| December | 34 | 36 | 31 | 62 | 725 | 124 | 1,001 |
| January | 33 | 35 | 31 | 31 | 756 | 93 | 1,094 |
| February | 35 | 37 | 28 | 84 | 840 | 140 | 1,234 |
| March | 36 | 38 | 31 | 124 | 964 | 186 | 1,420 |
| April | 37 | 39 | 30 | 150 | 1,114 | 210 | 1,630 |
| 15 May | 43 | 44 | 15 | 165 | 1,279 | 180 | 1,810 |

[a]TUS = (X daily temperature – 32) (days).
= (45 – 32) (16) = 208.

energy that is consumed might be available for growth. Accordingly, if hatchery data are used, relative instead of absolute values should be reported for comparisons of temperature regimes.

*Step 3.* Calculate size (Table 10). For example, at the end of April the estimated size of regime A fish would be 6.74 cm, compared with 5.42 cm for regime B. Assuming that growth was based on hatchery conditions, relative values should be reported (i.e., predicted growth in length would be about 24% higher for regime A).

Length information can be used to estimate the biomass of surviving fish by using length–weight tables (Piper et al. 1982). For example, from table values for chinook salmon the biomass under regimes A and B, assuming that 10,000 fish are produced, is about 25 kg and 13 kg, respectively. This represents about 92% more biomass for regime A.

Note that this example is based on regimes within the temperature range recommended by Reiser and Bjornn (1979) for juveniles. If temperatures exceed the maximum range temperature, growth rates would begin to diminish. Brett et al. (1982) reported that this temperature would be 14.8° C for spring chinook salmon (Fig. 5). At about 18.5° C there was sublethal growth stress, defined as growth rates 20% less than those for optimum conditions. Accordingly, to prevent sublethal growth stress the recommended upper limit is 14.8° C. The rationale is that when growth stress occurs, fish are more susceptible to disease and other problems, resulting in increased mortality rates.

Table 10. *Use of monthly thermal unit data to estimate juvenile size for two flow regimes. One centimeter of growth required 9.9 MTU's for all 3 months, and it was assumed the fish averaged 3 cm on 1 February.*

| Month/regime | Mean monthly water temperature | Monthly thermal units | Growth[a] | End of month size (cm)[b] |
|---|---|---|---|---|
| February | | | | |
| A | 39 | 7 | 7/9.9 = 0.71 | 3.71 |
| B | 33 | 1 | 1/9.9 = 0.10 | 3.10 |
| March | | | | |
| A | 46 | 14 | 14/9.9 = 1.41 | 5.12 |
| B | 42 | 14 | 10/9.9 = 1.01 | 4.11 |
| April | | | | |
| A | 48 | 16 | 16/9.9 = 1.62 | 6.74 |
| B | 45 | 13 | 13/9.9 = 1.31 | 5.42 |

[a]Growth = MTU's per month ÷ MTU's per centimeter of growth.
[b]Size at beginning of month plus monthly growth.

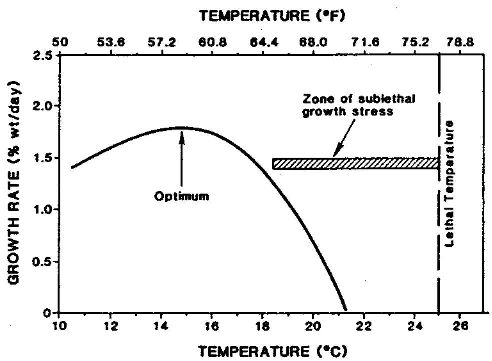


Fig. 5. Relations between temperature and growth rate for chinook salmon. The curve is for experimental rations (60% of the satiation level) thought to correspond to food availability in the Nechako River, British Columbia (Brett et al. 1982).

## Option 3: Population Statistics and Predicted Responses to Simulated Temperatures

This option requires compiling temperature envelopes similar to those reported by Hokanson and Biesinger (unpublished report). The major difference is that instead of developing standard envelopes with use of data obtained throughout the geographic range of a species, they are developed for a specific stream (Fig. 6).

The rationale for the envelope concept is that population statistics would not change if simulated temperatures match historical conditions. Statistics refer to two categories: measurements of success and well-being, and special status. The first category includes adult size, growth rate, yield, population number, or net production (Ricker 1968). The second category refers to rarity in a geographic area, and rare and endangered.

In some streams, temperatures (e.g., those for spawning, incubation, rearing) might be ideal, producing highly successful populations. In other streams, however, temperatures might be substandard but a population can still be successful. This situation may be attributed to some form of compensation, such as the presence of superior spawning substrate, abnormally low predation rate, excellent water quality, high food production, or possibly genetic adaptation that causes higher than expected population success. Another possibility is that temperatures can be marginal and impair success, but the status of a population can be very important (e.g., the only one in a geographic area) and a top priority for protection.

If differences are predicted for a new regime, judgment must be exercised to evaluate possible effects. One option is to compare the extent of temperature difference and amount of the time the altered temperatures fall outside the recommended range and tolerance range values (Table 6). Although some of these values can be exceeded under existing conditions, changes outside the reported tolerance range could have serious effects and should be avoided. For example, suppose a stream produces large spring chinook salmon smolts, although the existing temperature regime may be occasionally marginal during the growth period; the reason may be lack of interspecific competition that functions as a compensating factor. If simulated temperatures for a new regime were higher (Fig. 7), problems may occur. For example, from late June to late August (Fig. 7) under the simulated new flow regime, temperatures can increase beyond reported tolerances for adult migration, spawning, incubation, and rearing. This can be grounds for negotiating flows to avoid additional temperature increases.

This approach resembles the one used by Wilson et al. (1987) to evaluate effects of proposed dams on Alaska's Susitna River. However, they used weekly means (historical and simulated) instead of envelopes. They stated that tolerance temperatures for spawning would be exceeded for 1 week under the new regime, but long-term adverse effects were not predicted. Conversely, the predicted new temperature regime would exceed lower tolerances for juvenile growth during part of the year. Using growth

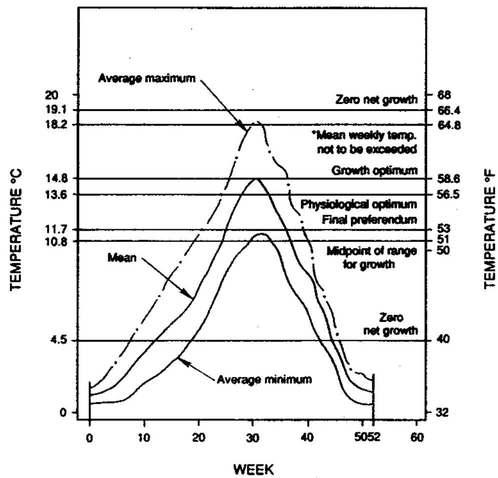


Fig. 6. Example of a temperature envelope. The data are for U.S. Geological Survey gauge station number 13293800 for the Upper Salmon River near Red Fish Lake in Idaho. Zero net growth and other experimental response data (Table 2) for juveniles are included. The upper MWAT of 18.2° C calculated with Brett's (1982) experimental optimum temperature value for juvenile spring chinook salmon is exceeded.

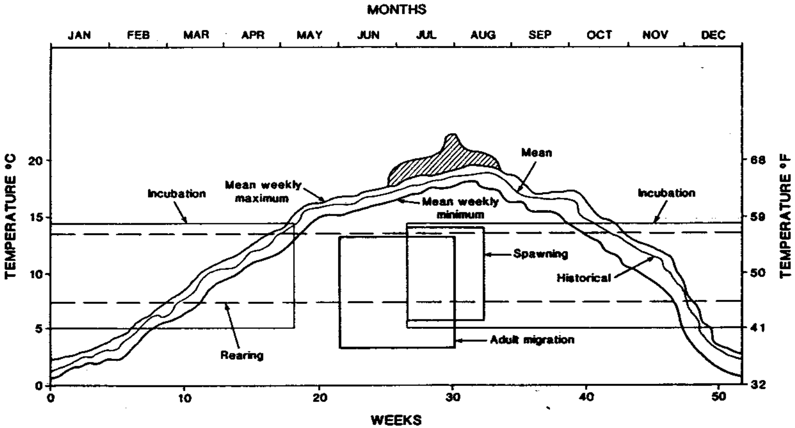


**Fig. 7.** Results comparing historical and simulated temperatures for a hypothetical spring chinook salmon stream. The *stippled* zone represents the period when the range of mean weekly maximum temperatures for the simulated regime would exceed existing conditions.

tables developed by Brett (1974) led to the conclusion that growth would be adversely affected (Wilson et al. 1987). This option could be used to evaluate effects of alternative actions under consideration. For example, if altered flows are considered, temperatures for the flows could be simulated. Then comparative data could be developed to recommend the preferred alternative, as was demonstrated in the example for option 2 (Table 7).

## Concluding Guidance

Before deciding which procedure to use for evaluating a new temperature regime, characteristics of the three options should be compared (Table 11). Regardless of the option selected, acquisition and assembly of necessary information can be a formidable task if literature sources are unknown or other data do not exist. To aid in coping with this type of problem, an expert familiar with life history requirements and information sources for the species of concern should be consulted. A good approach for identifying appropriate experts would be to contact aquatics specialists associated with local universities, State fish and game agencies, and the U.S. Fish and Wildlife Service's Cooperative Fishery Research Units. Additionally, contact could be made with persons in the National Marine Fisheries Service or the Fish and Wildlife Service's National Ecology Research Center to obtain information. If it is infeasible to acquire and assemble necessary information, a field person could use this document to scope a work order for a contractor to complete. Then, a recommendation concerning an acceptable temperature regime could be made after evaluating the contractor's information.

Regarding emphasis on elevated temperatures, it should be clear that low temperatures also must be a concern. A prime example of effects from low temperatures can be in zones below dams from which cooler water is released. In these zones, some species can be replaced, and success of others can be impaired. Therefore, if a proposed project is predicted to lower temperatures, this is not justification for assuming that adverse effects will not occur. Instead, species of concern should be specified, and an impact analysis should be performed.

If impact predictions are made using equations given here (e.g., MWAT), remember that calculated results are not absolutes. For example, the calculated conservative MWAT for rearing of spring juvenile chinook salmon (refer to page 4) is 15.6° C. Some hatcheries and streams exceed this temperature to a moderate degree; however, fish populations are successful. This emphasizes relying on temperature information applicable to local conditions, and accounting for factors including natural variation, compensation, and other site-specific phenomena.

Before initiating stream temperature evaluations, it is necessary to approve the methods to be used in negotiations. This will ensure that problems will not arise because of method biases. Also, this guidance should not be used as a reason for advocating that temperature information must be acquired for all species. For example, suppose that Option 3 is applied, and it is known that, historically,

Table 11. *Comparison of options.*

| Options for basis of temperature recommendations | Distinguishing features | Required information | Comments |
|---|---|---|---|
| 1. Experimental temperature tolerance results | Simulated temperatures for specific life stages (e.g., rearing) periods would be used to determine permissible maximum weekly temperatures, short-term exposures that could be tolerated, lethality of an exposure time for a given temperature, and survival time for an exposure temperature. | Experimentally derived temperature information (e.g., for growth, tolerance, physiological optimum, and final preferendum) must be obtained from literature sources. To apply the option, simulated temperatures (e.g., a maximum daily temperature during the growth period) are required. | Special care must be taken to ensure that appropriate experimental data are used. For example, if the juvenile life stage is the concern, use of data for that stage is necessary. |
| 2. Suitability of a simulated temperature regime for key life stages<br><br>Brungs and Jones | Heavy reliance would then be on evaluating simulated regimes in terms of compliance with recommended temperatures and tolerance ranges for key life stages. | Recommended temperatures and tolerance ranges for key life stages and functions (e.g., adult migration, spawning, incubation rearing) must be assembled from literature sources. Also, simulated temperatures are required. | Key starting points for obtaining life history information pertaining to temperature requirements are Habitat Suitability Index models[a] and habitat suitability index curves: Brown (1974), Hokanson and Beisinger (unpublished report), Brungs and Jones (1977). |
| 3. Population statistics and predicted responses to simulated temperatures | The option can be applied to evaluate deviations from an existing regime in terms of possible effects on the known status of a population. The feature is important because situations might be: (1) successful in spite of substandard temperatures due to some form of compensation, or (2) less successful because of adverse temperatures but important (e.g., rare in a geographic area) and the objective is to maintain or improve their status. | Data documenting the existing status of a population (e.g., population number, size of adults for trophy fishing, net production, rarity) plus temperatures for historical and simulated conditions are required. Also, recommended temperature ranges and tolerances for key life stages must be known to evaluate effects of simulated temperatures from existing conditions. | This option is similar to Option 2 except that emphasis is on population statistics. If an envelope is developed it would be applicable to other species if it is known that they are successful in streams from which data are obtained. For example, steelhead and spring chinook salmon can be successful in the same stream. |

[a]Information relating to species for which Habitat Suitability Index models and suitability index curves are available can be obtained from the U.S. Fish and Wildlife Service, National Ecology Research Center, Fort Collins, Colorado 80525.

conditions are suitable for maintaining a fish community. Accordingly, if temperature regimes are not altered as a result of a proposed action, additional information and analyses would be unwarranted. This would not mean that temperature requirements for all life stages and periods for the stages would be identical for all species. Provided a regime does not differ markedly from historical conditions, the appropriate interpretation would be that it should be suitable for continued fish community success. Conversely, if temperatures are predicted to be outside the historical envelope, specific information should be obtained before making recommendations for stream flow and temperature.

Merely considering mean temperatures can prevent serious problems from being detected. For example, suppose that mean daily temperatures for the first week of July in a spring chinook salmon stream were 24.0° C, 13.5° C, 14.5° C, 13.8° C, 13.1° C, 14.0° C, and 15.0° C. The mean weekly temperature would be 15.41° C. This value would not exceed the conservative MWAT value (15.6° C) for juvenile chinook salmon growth. However, if effects of the highest temperature of 24.0° C for a 24-h period are considered by using equation (7), lethality would be predicted because 1.3 exceeds unity.

Finally, an analysis should account for the importance of separate stream reaches. All reaches may not be equally important for all life stages of a species. For example, spawning and incubation might occur in an upper reach where temperatures are cooler than in a lower reach where rearing occurs. Also, within a stream, a natural gradient of increasing temperature often occurs from headwaters to lower reaches (Hynes 1972). This consideration is important because discrete zones with regimes suitable for distinctly different fish communities and activities can exist.

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[1] The date on the publication that C. M. Tarzwell edited is 1960, Brett's title conflicts.

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